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Numerical Investigation of Supersonic Channel Flow with Oscillatory Backpressures

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Abstract. The investigation of supersonic channel flow with periodic oscillatory backpressures at the outlet of the channel was performed using large-eddy simulation for the inlet free-stream Mach number 4 and the Reynolds number approximately 5.2×10^4 based on the height of the channel. Results have been validated carefully against our experimental data. Three typical backpressures are considered for constant backpressure and both periodic oscillatory backpressures with low and high frequency. The oscillatory backpressure can obviously influence the flow features occurring up to the middle region of the channel for the low frequency case and the downstream region for the high frequency case. Obvious differences of phase-averaged quantities at different phases are observed for the low frequency backpressure while the differences are relatively small for the high frequency backpressure. The spectral analysis reveals that the flow field experiences a periodic-like evolution of flow structures including shocks and vortices for the low frequency backpressure, resulting in the enhancement of turbulence fluctuations due to the complicated interaction of shocks and vortices.

AMS subject classifications: 76F65, 76L05, 76F70

Key words: Large eddy simulation, shock wave, turbulent flow.

1 Introduction

The supersonic air breathing propulsion system includes the inlet and the isolator which are the precombustion compression components [1, 2]. In the inlet, the incoming flow is compressed through a series of shocks before entering the combustion chamber. To isolate the effect of flight conditions on the precombustion shock structure, a nearly parallel walled duct named isolator is placed between the inlet and the combustor [3–5]. The isolator contains a time-varying shock train system providing a stable flow to the

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combustion process and is highly susceptible to the flow induced instabilities. Hence, the pressure change caused by the combustion will lead to complicated flow phenomena and mechanisms in the isolator [6].

The unsteady properties of the internal flow caused by high backpressure were investigated. Wagner et al. [7] dealt with the dynamics of internal flow influenced by the backpressure generated by a deflecting flap at the downstream end of the isolator by means of the PIV measurement and observed that the unsteadiness of the internal flow is associated with boundary layer separation. Tan et al. [8] experimentally investigated the unstart flows of a rectangular hypersonic inlet at a freestream Mach number of 5 and demonstrated the typical external/internal flow patterns and the unsteady behaviors of surface pressures. Recently, Li et al. [6] designed a two-dimensional hypersonic inlet/isolator model to investigate the complicated flow structures experimentally. They found that the upstream-propagating shocks in the isolator play an important role on the flow properties and the formations of the upstream-propagating shocks are related to the downstream-propagating compression waves/shock waves that encounter the throttling section.

On the other hand, some numerical simulations were carried out to investigate the flow behaviors in the inlet-isolator system. Koo et al. [5] performed a large-eddy simulation (LES) of the Mach 5 inlet-isolator system adopted by the experiment [7]. Two cases including a started isolator and transient unstart propagation were considered to analyze the characteristics of flow separation and shock waves. It is demonstrated that the LES technique is able to predict fully started flow accurately and to capture the large-scale features of the unstart process. Ingenito et al. [9] also performed the LES of the HyShot combustor system to analyze the effects of mixing and combustion. Cocks et al. [10] carried out a detached-eddy simulation (DES) of supersonic combustor to study the characteristics of the cavity flameholder and identified that the prescription of inflow turbulence plays an important role on the accurate prediction of the shock train. Krishnan et al. [11] also performed the LES of Mach 8 inlet system to analyze the transition mechanisms on the compression ramps and the statistical characteristics of the flow field.

Actually, the backpressure caused by the combustion downstream has remarkable variation. Although the unsteadiness of the internal flow in an isolator has been widely investigated, the situations with periodic oscillatory backpressure are rarely studied. Bur et al. [12] performed an experiment on the periodic motions of shocks in transonic channel flow, where the motion was generated by the rotating elliptical or rectangular shaft at the exit of the channel. The influence of the rotating shaft shape on the shock oscillation in the channel was investigated. Based on the experimental measurement, the numerical simulation by means of the two-dimensional unsteady Reynolds-averaged Navier-Stokes (RANS) solution was also done. Further, Bruce and Babinsky [13] experimentally investigated an oscillating normal shock wave subjected to unsteady periodic forcing in a duct, where the periodic backpressure was generated by an elliptical cam placed in the downstream of the duct. The interaction between the moving shock and the boundary layer was analyzed and an inviscid analytical model was proposed to reproduce the dynamics